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FLOATING TUNNEL FOR LONG WATER CROSSINGS

By Charles E. Andrew, M. ASCE

STRUCTURAL DIVISION

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PAPERS

FLOATING TUNNEL FOR LONG WATER CROSSINGS

By Charles E. Andrew,[1] M. ASCE

Synopsis

The rapidly advancing requirements of vehicular transportation, caused by increased population and industry, occasionally necessitate an engineering attempt to span water barriers which formerly were considered either impossible to cross or economically unsound. The purpose of this paper is to present a preliminary study of such a problem. The solutions suggested and presented are by no means to be considered final in detail. It seems to the writer, however, that they do present the only possible method of constructing a vehicular bridge between the points indicated. Briefly stated, the problem presented to the writer, by the Director of Highways of the State of Washington, was to make a study of possible methods, if any, of constructing a permanent highway structure across Puget Sound between Seattle, Wash., on the east and the mainland on the west shore.

Territory and Population to Be Served

The immediate territory in the State of Washington to be served by the proposed facility includes the rapidly growing City of Seattle on the east shore and the City of Bremerton and Kitsap County on the west shore. The metropolitan population of Seattle is more than 500,000 (1949) and that of Bremerton and Kitsap County approximately 90,000. In addition, the entire north end of the Olympic Peninsula, containing approximately 5,000 sq miles lying to the west and including the Olympic National Park, is tributary to such a crossing. The present total population, on the west shore, is approximately 120,000. However, this population cannot be considered to represent the number of motorists who would use such a crossing within a few years after its construction, as a very large area of some of the most desirable residential property in the state, with hundreds of miles of shore line, would be made available to people who now refuse to be subjected to the inconvenience and

Note.—Written comments are invited for publication; the last discussion should be submitted by August 1, 1950.

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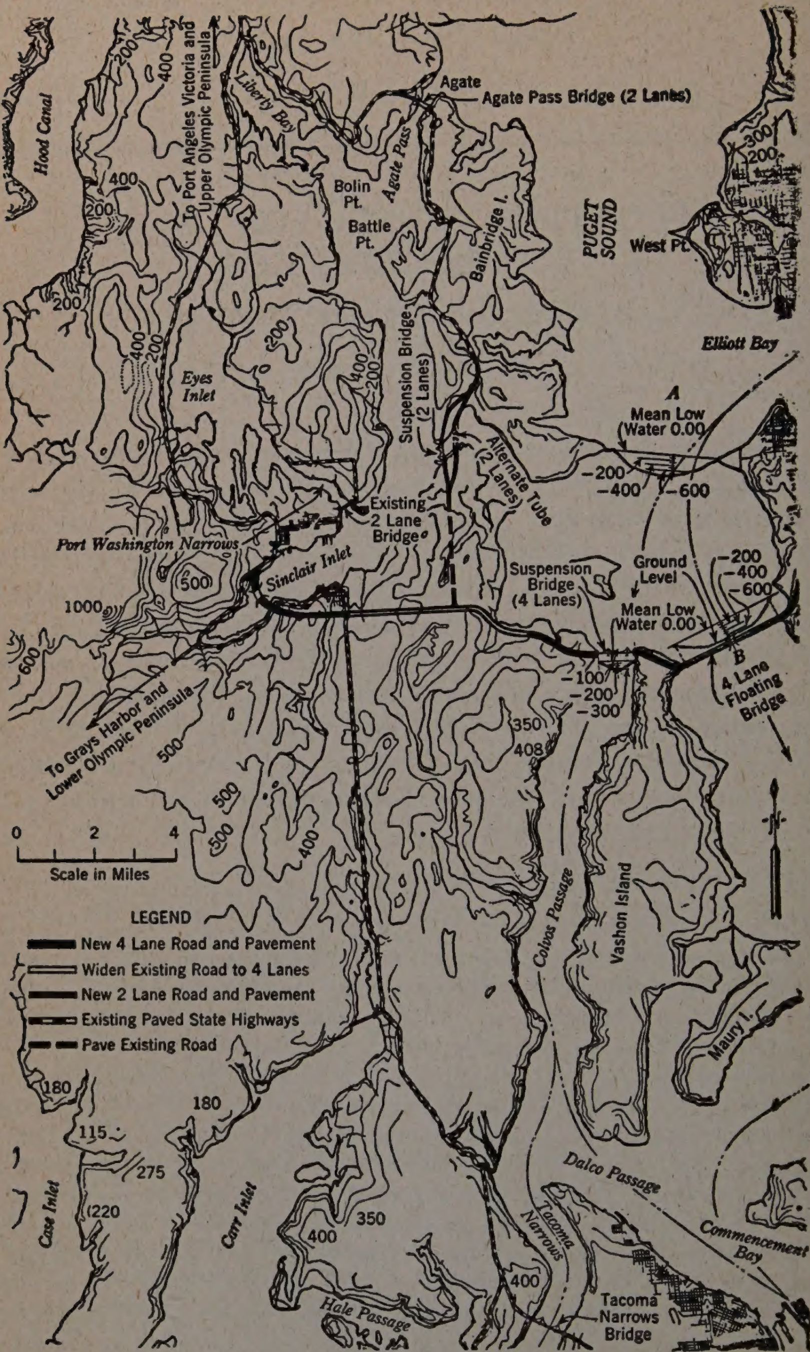

Fig. 1.—Project No 1, Proposed East–West Crossing of Puget Sound

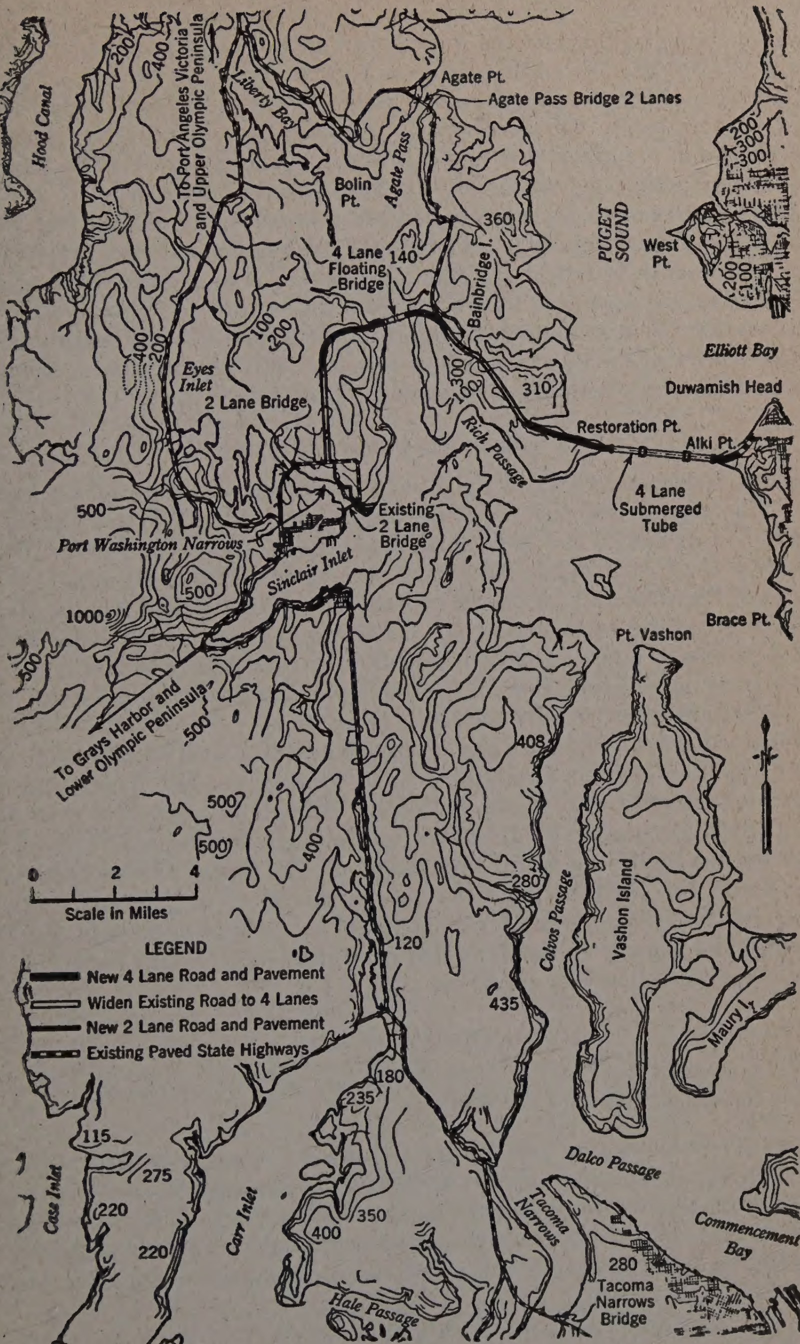

Fig. 2.—Project No. 2, Proposed East–West Crossing of Puget Sound

delay of ferry traffic. With a permanent uninterrupted crossing available, it is reasonable to believe that the west shore would develop a tributary population of at least 200,000 within 3 years or 4 years after completion.

The City of Seattle, as well as the State of Washington, will experience a rapid growth due to the development of cheap power and large irrigation projects east of the mountains, and it is reasonable to believe that Seattle will have a metropolitan population of 650,000 within the next decade.

The present ferry system has been a constant subject of criticism for many years. Rates have been high and recently have become almost prohibitive. Thus, the west shore is facing a stalemate, as far as future development and the badly needed expansion from Seattle are concerned.

It was for this reason and furthermore in the interest of badly needed future development that such a study was undertaken. Other economic factors are discussed subsequently under the heading, "Economic Studies."

Physical Conditions

Puget Sound is an arm of the Pacific Ocean and therefore is salt water. The tidal range in the vicinity of Seattle is from −3.5 ft to approximately +14 ft, a range of 17.5 ft. Tidal velocities at the sites considered are relatively low due to the fact that the tidal prisms are greater than those in several other reaches of Puget Sound. A maximum velocity does not exceed 2 miles per hr.

Three sites have been considered. As shown in Figs. 1 and 2, water depths over distances of approximately 10,000 ft vary from 600 ft to 800 ft. As a consequence, all consideration of piers must be abandoned as impossible and the water itself must be resorted to as a foundation.

Wind velocities of 80 miles per hr may be expected with normal maximum yearly velocities of from 55 miles per hr to 60 miles per hr. Wave action is choppy in character with maximum heights (trough to crest) of 8 ft or 9 ft. Ocean swells are practically dissipated before they reach Seattle. Depths of water for the study are taken from maps of the United States Coast and Geodetic Survey (USCGS); and the bottom condition, as indicated on these maps, is soft on the surface. The maps have been found to be very accurate but, of course, many of the foregoing conditions will require careful check before final determinations are made.

Results of Studies

Fundamental Considerations.—At the beginning of this study, seven fundamental considerations were self-evident:

(1) The water depths were so great that all thought of a structure supported by piers was useless, except in Calvos Passage, site A (see Fig. 1).

(2) Since the waters of Puget Sound constitute shipping lanes to Seattle, Tacoma, Olympia, and Bremerton, any structure must provide uninterrupted navigational channels of sufficient width and clearance for ocean going vessels of any size.

(3) At all sites, some part or all of the structure must be supported by flotation.

(4) All anchorage members must be of such construction and material as would resist corrosion in sea water indefinitely.

(5) The added weight of the marine growths, present in Puget Sound waters, must be accounted for.

(6) Construction must insure against any considerable degree of leakage.

(7) A prospective future annual traffic of 10,000,000 vehicles requires four traffic lanes.

Possible Sites.—Examination of maps indicate that three possible sites are available. Two sites A and B are shown in Fig. 1. Site C to the north is almost identical with site A.

The center line of site A runs between Alki Point on the east shore to Restoration Point on Bainbridge Island, a distance of approximately 14,800 ft from shore to shore. A structure at this location would cross the only sea lane to Tacoma, Bremerton, and the southern end of Puget Sound. Therefore, it must permit unobstructed passage of ocean shipping. The depth of water, over 10,000 ft of the total distance, averages 700 ft with a maximum depth of 800 ft.

Sites B_1 and B_2 involve two main channels of Puget Sound. Each site leaves the easterly shore at Brace Point crossing over East Passage to Dolphin Point on Vashon Island, a total distance between shore lines of approximately 14,000 ft (see Fig. 1). For 11,000 ft of this total distance, the water depth averages 600 ft. From Vashon Island the line crosses Calvos Passage from Point Vashon to Point Southworth, a distance of approximately 4,600 ft. Maximum water depth at the center of the channel is 340 ft.

The center line of site C runs from West Point on the east shore to Skiff Point on Bainbridge Island, a distance of approximately 15,600 ft. This site (which is not shown in Figs. 1 and 2) is north of Elliott Bay and consequently crosses the only sea lane to Seattle, Tacoma, Bremerton, and the southern end of Puget Sound. Water depths are practically the same as those for site A. In any case, Bainbridge Island will be connected to the west mainland by bridges over either Port Orchard Bite or Rich Passage. From a traffic utility point of view, sites A and C are approximately equal and have a slight mileage advantage over site B. The latter, however, serves a larger potential population in that it affords a direct outlet from Vashon Island to the east and west.

Type of Proposed Structures at Site B.—Two types of structure are proposed over the East Passage (see Fig. 1). In one case, it is assumed that a permit can be obtained to close the east channel to ocean shipping with the exception of one 400-ft movable span in the main channel and that unobstructed passage of small boats near either shore line can be provided. The structure would consist of a floating type similar to, but of deeper draft and heavier wall construction than, the Lake Washington Bridge.[2] Main shipping lanes would be diverted to Calvos Passage where unobstructed passage would be provided under a 3,300-ft central span suspension bridge with the same vertical clearance as provided at the Tacoma Narrows Bridge.[3] The travel distance by boat to

[2] "Building the World's Largest Floating Bridge," by Charles E. Andrew, *Civil Engineering*, January, 1940, p. 17.

[3] "Unusual Design Problems—Second Tacoma Narrows Bridge," by Charles E. Andrew, *Transactions*, ASCE, Vol. 114, 1949, p. 955.

Tacoma and Olympia is shorter by Calvos Passage than by the east channel and tidal velocities are comparable.

In the second case, if the aforementioned permit cannot be obtained, the east channel would be spanned by a twin tube structure with 50 ft of submerged clearance under mean lower low water and Calvos Passage would be spanned by a surface floating structure similar to the Lake Washington Bridge.

Type of Proposed Structures at Either Sites A or C.—Inasmuch as ocean shipping must be maintained at both sites A and C, the only type of structure possible is a floating tube providing 50 ft of clearance over its top. Obviously such a tube must receive its support through buoyancy as it would be impossible to rest it on the bottom of Puget Sound in water as deep as 800 ft. A filled base would be "out of reason" and would restrict the tidal prism to such an extent that tidal velocities would be prohibitive.

The three sites thus briefly described are the only ones that can be considered, because of the much greater length of crossings at any other points within a reasonable distance from the center of population of Seattle.

A surface floating structure over the east channel, combined with a long suspension span with high clearance over Calvos Passage, is without doubt the most conventional solution as both types of structures are well established by precedent (see Fig. 2). Such a structure requires an expenditure of funds considerably smaller than that required by other structures and, because of its location, is only slightly inferior as a traffic artery. It does have a bearing on water traffic, however, in that the main shipping lane south of Seattle must be shifted from the east passage to the west passage. The latter is not nearly so wide as the east passage although it is a more direct and slightly shorter route to Tacoma and a much more direct and shorter route to Olympia.

Whether or not a permit could be obtained for such a crossing has not yet been determined. No doubt a permit to build the submerged tube would be easier to obtain because it does not interfere with presently used navigation routes.

The Tube.—The writer recognized at the outset that the type of structure proposed may be considered rather bold; it presents many new problems in design, yet the general principles are relatively simple. Water is probably the most dependable of all foundation materials provided its laws of action (all of which are definitely known) are adhered to. The general principle that governs the design is restrained flotation.

Tube sections are designed as shown tentatively in Figs. 3 and 4 with such weight and dimension that, when bulkheaded at the ends, they will float well above water. Sufficient excess buoyancy of the tube section is provided so that it is equal to two and one-half times to three times the maximum amount of live load—which, in this case, includes vehicular traffic, weight of marine growths, vertical components of tidal anchors, etc.

To accomplish this purpose safely, careful computation of weight and displacement is necessary. An interesting side light is the maximum submerged weight that may be expected from marine growth.

A dense concrete, made of cement resistant to the harmful effect of sea water with deeply embedded reinforcement, has been selected. A minimum

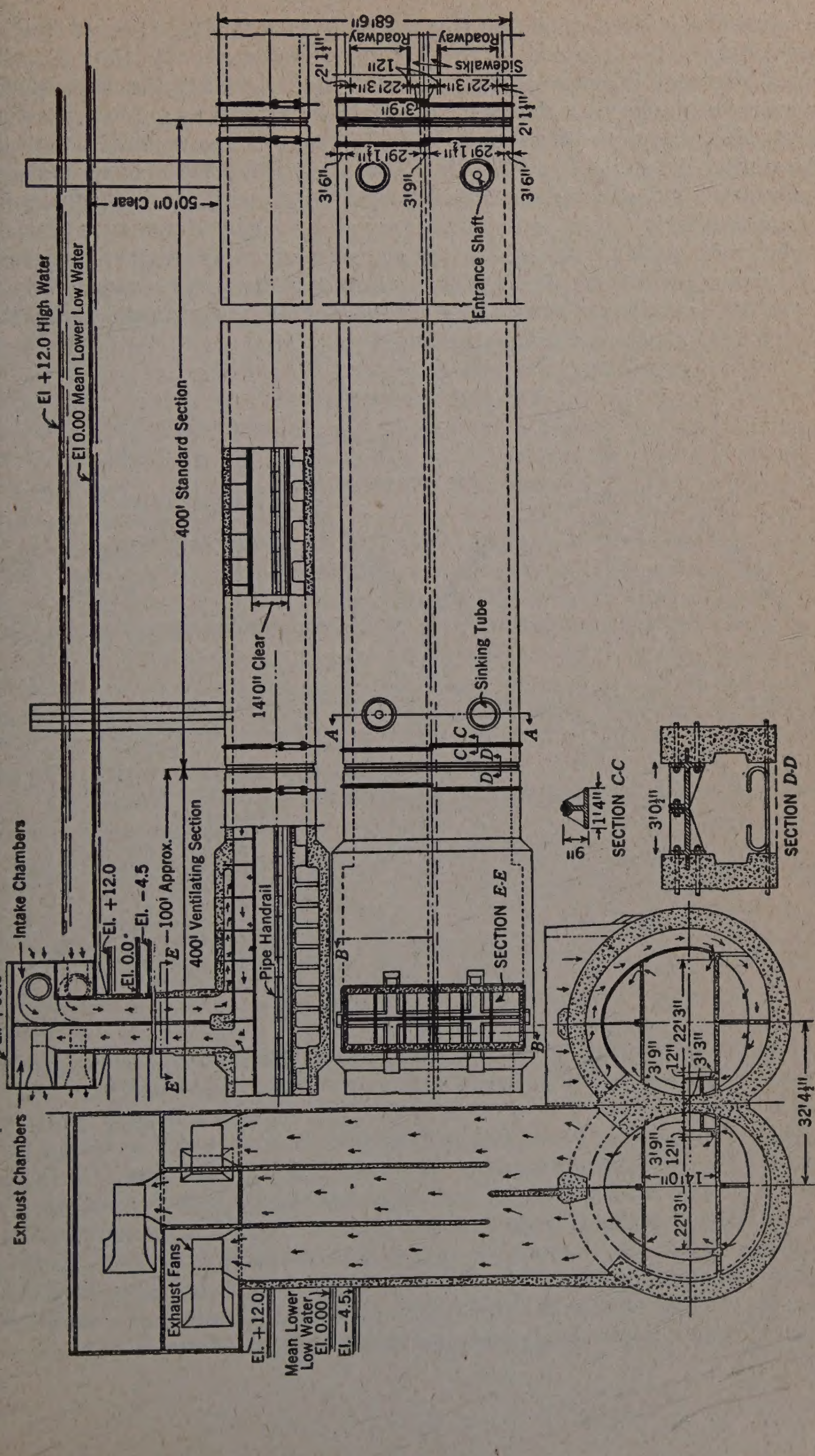

FIG. 3.—PRELIMINARY PLAN, FLOATING TWIN TUBES

thickness of tube shell equal to 3 ft is necessary to obtain the required weight that will keep the live-load anchors within a reasonable size (Fig. 4). In general, the shell thickness is determined by the weight and the accessibility for concrete placement rather than by stress considerations. Moments and shears, of course, determine the steel reinforcement. The required length of tube section (for example) at site A is 13,600 ft, with 2,300 ft of open shore approaches. This extreme length necessitates forced ventilation. A minimum of four ventilator towers is required—one at each end of the tube section forming the junction between floating and open shore approaches, and two in the main channel which must be floating with the tube section. These two floating ventilating towers offer an interesting and somewhat difficult problem. Fig. 3 shows a proposed solution.

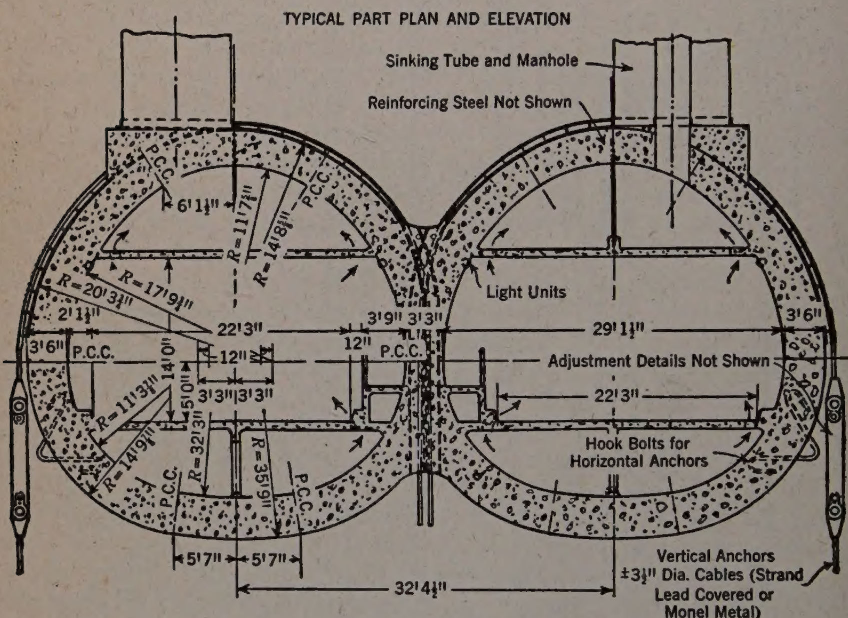

FIG. 4.—SECTION A–A, ENLARGED SCALE

Flotation and weight problems are fully susceptible to calculation. Cross sections of the towers below the powerhouses are made as small in area as possible within the area of tidal range to effect a minimum change in flotation due to the rise and fall of tide; and lightweight aggregate is used in the towers above the tube to decrease weight. The danger of ships colliding with these towers is of extreme importance; and, to guard against such a contingency, massive floating fenders of deep draft, firmly anchored at a considerable distance away from the towers, and completely surrounding them, are provided.

These fenders will weigh approximately 30,000 tons each. They not only will resist the impact of ship collision but will form a calm lagoon around the towers, impeding tidal velocity and eliminating wave pressures.

Live-Load Anchors.—Live-load anchors are required directly below the tube, on the bottom, to resist the tube uplift. For the most part, these anchors rest on a rather soft bottom material and are in water depths as great as 800 ft. The tentative design contemplates a flat shallow anchor spread over a comparatively large area. In principle, this anchor simulates the sole fish which lays on the bottom for long periods in swift tides without causing appreciable scour. It will have an underwater weight of from 500 tons to 600 tons and will exert a bottom pressure of approximately 500 lb per sq ft when attached to the submerged tube.

To construct and locate this type of anchor with reasonable accuracy, it is first necessary to design and construct a steel shell on shore which can be floated to the proper position and lowered to the bottom by derrick after water is admitted. The weight of such a shell will approximate from 60 tons to 70 tons under water. The shell is constructed with large open hatches in the top. Heavy cross frames and longitudinal trussed frames intersecting at points of attachment of the main hold-down cables are constructed as part of the shell framework in such a manner that they are wholly embedded in concrete when the shell is filled.

The main hold-down cables are finally attached to these frames before the shell is submerged and, as the shell is sunk, are unreeled from barges. When the shell is properly landed in position, the cables are laid out on the bottom with surface pendants attached; later they are picked up when the tube sections are brought into position. Before sinking the shell four lighter guidelines are attached, one at each corner of the hatches, which may be utilized to lower the shell to the bottom and later to act as guides for bottom-dump concrete buckets filling the shell. The outside shell of the anchor is considered temporary and can corrode away leaving the concrete anchor.

When tube sections are later towed into position, the large anchor cables or chains are picked up. One side of the anchor loop is long enough to reach above the water surface. This long end is threaded through a pipe insert provided through the intersection wall of the twin tubes. When the tube section is sunk to slightly below its final elevation, this anchor line (if a cable is used) is brought above the water and socketed to a known length. It is then looped over the tube section and attached with an adjustable-length connecting bar, to the short anchor line, by divers at the approximate level shown in Fig. 3. When all lines to a given tube section are connected, water is pumped from the tube and the section rises by flotation into the loops formed by the anchor lines. Tube levels are then checked and adjusted to the proper elevation at adjusting bars.

Lateral Anchors.—To hold the tube in alinement laterally against flood and neap tides, heavy bottom anchors, constructed in the same general manner as the live anchors, are provided.

A serious difficulty is the determination of what material should be used in both the live-load anchor lines and the lateral anchor lines since the water is salt and exceedingly corrosive. Maintenance of the vertical live-load anchor lines presents the greatest problem as it would be exceedingly difficult, if not impossible, to renew the lines. Two types of material have been considered—

(*a*) monel metal chains or cables and (*b*) lead shielded cables. Recent developments with titanium should be considered, although the cost would be excessive even if the metal were further developed.

It would be impracticable to use chains for lateral anchor lines on account of the weight and length; however, it is possible to develop a detail by which these lines can be renewed when necessary and the use of lead shielded steel cables or monel cables is proposed. In any case, extensive research will be necessary when, and if, funds and the opportunity to build this structure become available. Monel metal has been exposed successfully in salt water for many years and is probably the most promising material. It is felt that modern manufacturing, ingenuity, and metallurgy can satisfactorily solve the problem of corrosion.

General Plan and Method of Tube Construction.—The plan contemplates a twin tube of the general cross section shown in Fig. 4, providing four traffic lanes. The over-all length of the structure (site A) is approximately 15,900 ft, consisting of 1,150 ft of open approach at each end extending out to a point where the water is approximately 50 ft deep at low tide, and to the shore ventilating towers which are founded either on piling or on rock. The tube section, consisting of thirty-four sections, 400 ft long, extends across the sound between the shore ventilating towers for a distance of 13,600 ft.

The descending grade lines through the open approach structures are approximately 4%. From the shore ventilating towers, the grade lines continue on a 2.6% grade to points in the channel where a 50-ft depth below mean low water is reached over the crown of the tubes. A minimum of two additional ventilating towers is necessary in the main channel to divide the full length of the tubes into four sections of 3,400 ft each for the purpose of ventilation.

From a construction point of view, the proposed tube involves heavy special equipment and the solution and careful handling of details; yet, when analyzed, these features do not appear particularly difficult. The completed structure requires approximately 550,000 cu yd of concrete, of which 400,000 cu yd would be poured at a fixed mixing plant situated at the graving docks where the 400-ft sections of the twin tubes would be fabricated. As each 400-ft section is completed and set, bulkheads would be placed at each end. Water would then be admitted to the graving dock and the section floated into the sound.

Vertical sinking tubes are erected near each end of each tube (four in all). These tubes are attached to a connection framed into the tops of the tube sections and are of sufficient length to extend well above the surface of the water when the tube section is submerged to a depth of 50 ft under mean low water.

Before moving the section into deep water, tests for leakage are made by pumping a sufficient amount of water into the section to submerge it. Each section is then lowered by admitting additional water into the sinking tubes until the top of the tube section is 50 ft below water. This preliminary test is made at a point where the water is not deeper than from 90 ft to 100 ft. The section is permitted to stay in the submerged position for several days and

then is raised to the surface by pumping water from the sinking tubes. If no leakage has taken place, the section is ready to tow into its final position in the structure. Prior to placing any section, both the live-load anchors and the lateral anchors with lines attached are set in place. The open approach structures, including the shore ventilating towers, will also be completed while the graving dock is being constructed and while the first tube sections are being fabricated and tested.

Tube placement will begin with the first sections from each shore and will advance toward the center of the crossing. The first shore section will be attached to an especially designed expansion detail framed into the outer walls of the shore ventilating towers. This joint will not only permit longitudinal expansion but also slight lateral and vertical movement. The constant temperature of the sound waters will keep the longitudinal expansion small, the greatest possibility of change being near the ventilating towers. In this particular location, however, seasonal variation in air temperature is not great.

In principle, the final placement of tube sections is not difficult. The sequence would be as follows: A tested bulkheaded section is towed into position and the long side of the vertical anchor lines is threaded through the hawse pipes at each end of the section. Water is then pumped into the tube section until it is submerged, the lateral anchor lines having been first attached. The tubes are then sunk slowly by admitting water into them until a depth of slightly more than 50 ft over the top of the section is reached. The vertical live-load anchor line is then looped over the top and connected to the short end by divers at a carefully predetermined length.

The tube is lifted into the anchor line loops by pumping water from the sinking tubes, and preliminary levels are taken. If the tube is found to be either high or low in relation to its proper elevation, it is again lowered to slack the anchor lines and the proper adjustment is made at the connecting bars in successive operations until the proper elevation is reached.

The first shore sections are attached through the expansion detail to the wall of the ventilating tower which takes the vertical uplift of the section at the shore end while anchor lines resist the uplift at the outer or seaward end. Succeeding sections are sunk in a similar manner and attached by heavy cast-steel rings to the section already in place, proceeding from each end toward the center of the channel. A tentative connection is shown in Fig. 3. As each successive section is placed, bulkheads are removed via the shore ends and reused in other sections to follow. The connections are then completed by filling in the tube walls inside the cast rings, reinforcing steel being lapped to establish continuity.

To gain weight for sinking, and to reduce, as far as possible, the amount of water which would be required to overcome buoyancy in the sinking process, all the interior concrete (except that at the end connections) such as roadway slabs and curtain walls, would be poured at the graving dock.

On first thought, the matter of maintaining proper trim in sinking a freely floating section of this size and weight seems to involve a difficult problem. A tentative schedule for performing this task is as follows: First, removable steel tanks are installed while the section is in the dock. Tanks that would

contain from 70% to 75% of the sinking water required would be placed in the fresh-air duct below the floor, and tanks with a capacity somewhat greater than the remainder required would be placed on the roadway deck level.

The tanks in the fresh-air duct would be completely filled before the section is launched. The roadway tanks would be constructed with closely spaced watertight bulkheads dividing them into a series of small tanks. All tanks would be connected separately to a main pump line and an air line through valves; and the main water line and the air line would extend above the surface of the water through an entrance tube concentric with, and inside of one of, the sinking tubes.

This concentric tube would afford entrance to the section from the water surface at all times until the section is finally connected and entrance is established from the shore. The openings through the tube shell would then be closed by pouring concrete and the sinking tube would be removed for reuse on the following sections. As the test sinking starts, water is admitted to the closely bulkheaded roadway tanks, each compartment being filled symmetrically on each side of the longitudinal center of the tube beginning at the ends. In this manner, with all necessary tanks full, no end shifting of water can occur—final submergence, sinking, and trimming being accomplished by injecting additional water in the sinking tubes.

When the tube is finally sunk and the live-load anchor lines are connected, water is removed by compressed air in the reverse order of filling. The end connection is then made to the previous section; the sinking tubes are removed; and the bulkheads at the connected end are taken out through the shore end for reuse. Tanks are removed in the same manner. The end connection is then completed by filling in the ring of concrete inside the cast-steel connecting ring.

It is not possible to discuss further details in this paper. In fact, final plans have not been developed, and cannot be developed, until such time as further funds are appropriated to make a full investigation. The paper is intended merely to outline the fundamental principles of designing and constructing a structure which, in the writer's opinion, is the only type of crossing that can be devised to meet the physical conditions presently existing across Puget Sound.

Economic Studies

Quite extensive studies have been made to determine the economic feasibility of bridging Puget Sound between Seattle and the west shore. Census data are discussed herein under the heading, "Territory and Population to Be Served." Geographically, Seattle is situated on a relatively long narrow strip of land running north and south between Puget Sound on the west, and Lake Washington on the east. Its room for expansion is extremely limited by this fact. The unprecedented development to the east of Lake Washington and on Mercer Island, since the Lake Washington Bridge was completed, is evidence of the demand for more room. The bonds for the construction of that bridge were fully amortized in less than 10 years.

A situation now exists to the west of Seattle across Puget Sound, similar and parallel to that which existed on Lake Washington before the bridge was

built, except that there is a far greater amount of existing traffic west of Seattle. Hundreds of miles of the most desirable waterfront property is undeveloped with almost an unlimited amount of residential property available as far as urban development is concerned.

It is impossible to serve this area by ferries except at toll rates which are so high that further development of the area is practically impossible and expansion of Seattle in this direction is eliminated. With the prospect of free transportation within a reasonable period of years the picture is entirely changed. Property values alone will increase many times the cost of bridging Puget Sound, and this territory will be brought within reasonable driving distance of the center of Seattle.

Preliminary estimates of cost for bridging Puget Sound vary from $50,000,000 to $61,000,000 depending on the type of structure selected, the maximum cost being for the tube shown in Fig. 1.

For comparison of transportation costs between perpetual ferry operation and the proposed structures, a period of 35 years, including the period of design and construction, has been used. Costs include maintenance and operation. The average cost of transportation, including maintenance and operation, in dollars per traffic unit for continuous ferry service for a period of 35 years is found to be $0.4766. The comparable average cost of unit transportation for the same period for the proposed structure shown in Fig. 2 was found to be $0.1955. After 35 years, the cost would decrease to $0.015 per unit for maintenance. All bonds would be retired from 21 years to 22 years after issue. For the proposed structure shown in Fig. 1, unit costs for the first 35 years would average $0.2297. All bonds would be retired approximately 23 years after issue. After 35 years, the average cost of continuous ferry operation would decrease to approximately $0.35 per unit and would continue at that rate indefinitely. A unit of transportation is taken as a value representing one of the total number of passengers, automobiles, trucks, and buses crossing.

Conclusion

From the foregoing comparable estimates of average unit transportation costs which the writer considers as conservatively representing the economic picture, it is quite evident that bridging Puget Sound by either method is financially sound. The proposed structures reduce unit costs over the first 35 years, respectively, to 41% and 48% of ferry operation cost and after 35 years to 2.2% and 8.4%.

The type of crossing proposed may be regarded as rather daring and unusual. It involves many tricky problems and details. However, it is believed worthy of consideration and, in the end, entirely feasible.

The physical conditions existing at the available sites impose difficulties that would not be present in many other cases. For instance, if the water were fresh, problems of metal corrosion would be very much simplified. If water depths were less (say, from 150 ft deep to 250 ft deep), anchorage problems would be much easier. Crossings as long as 6,000 ft or 7,000 ft would not require floating ventilating towers, etc. In such cases the feasibility of the design is even more evident.